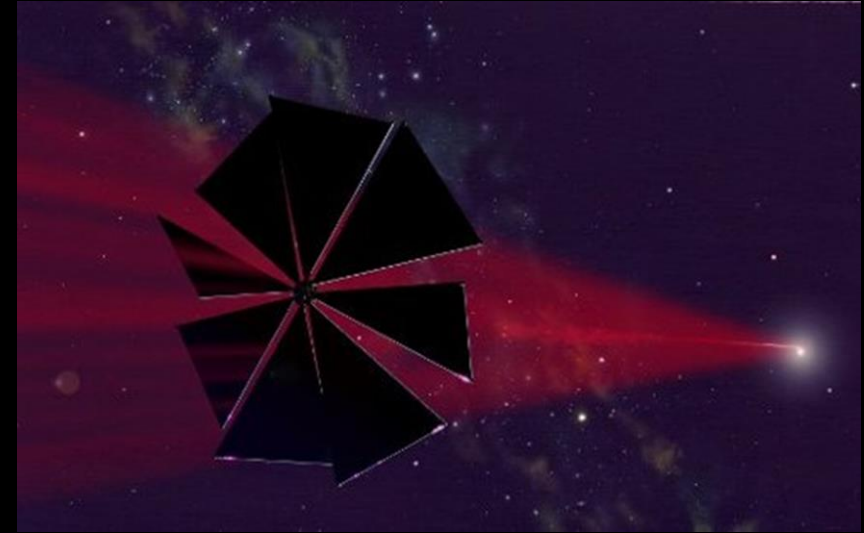
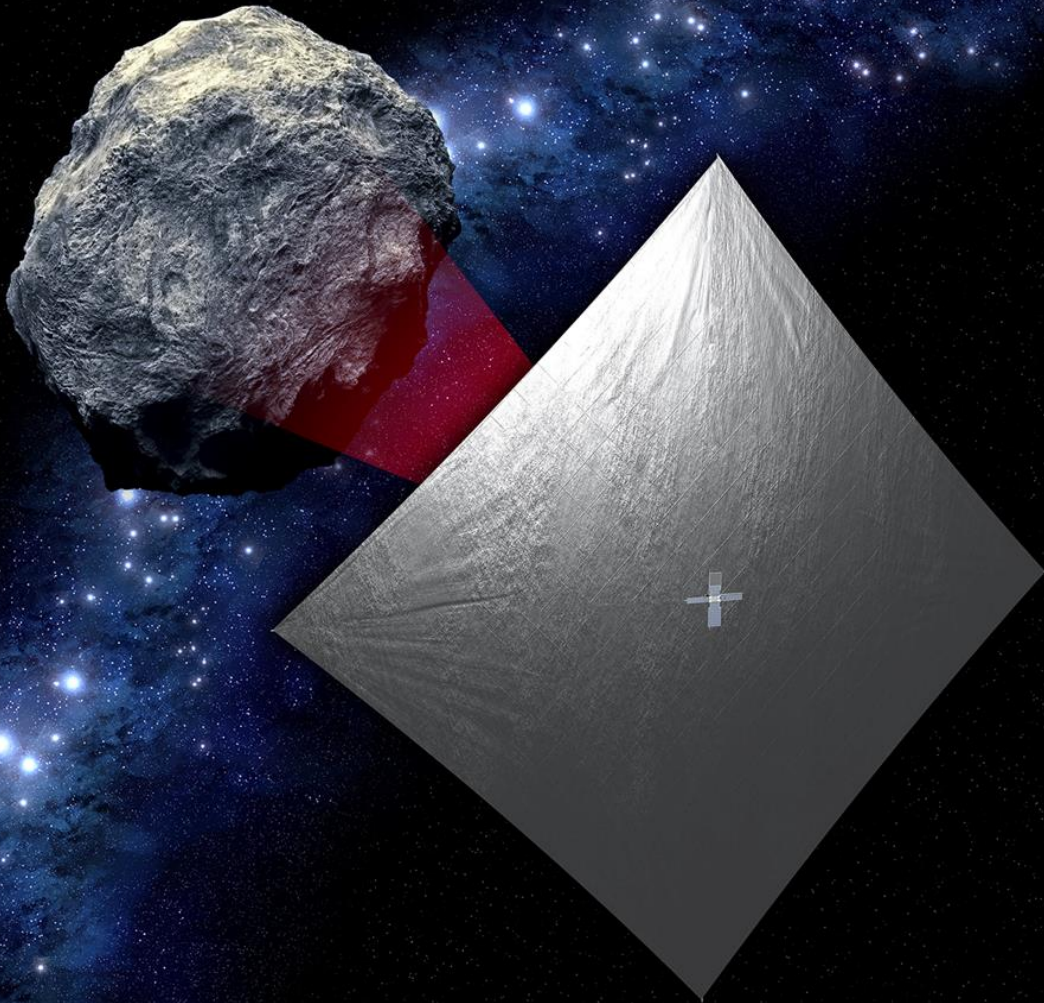




Solar Sails



Les Johnson

George C. Marshall Space Flight Center



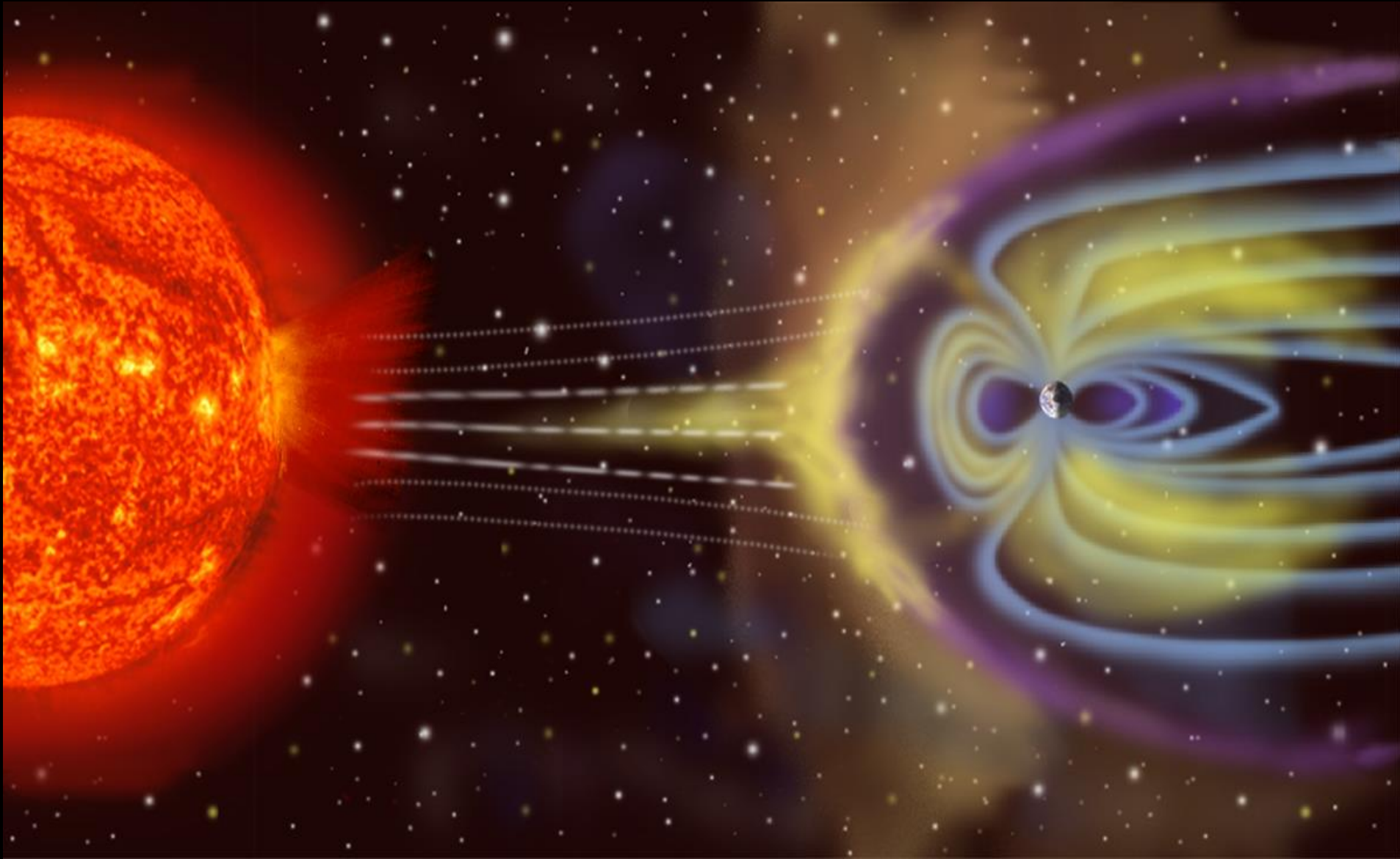
We tend to think of space as being

big and empty...





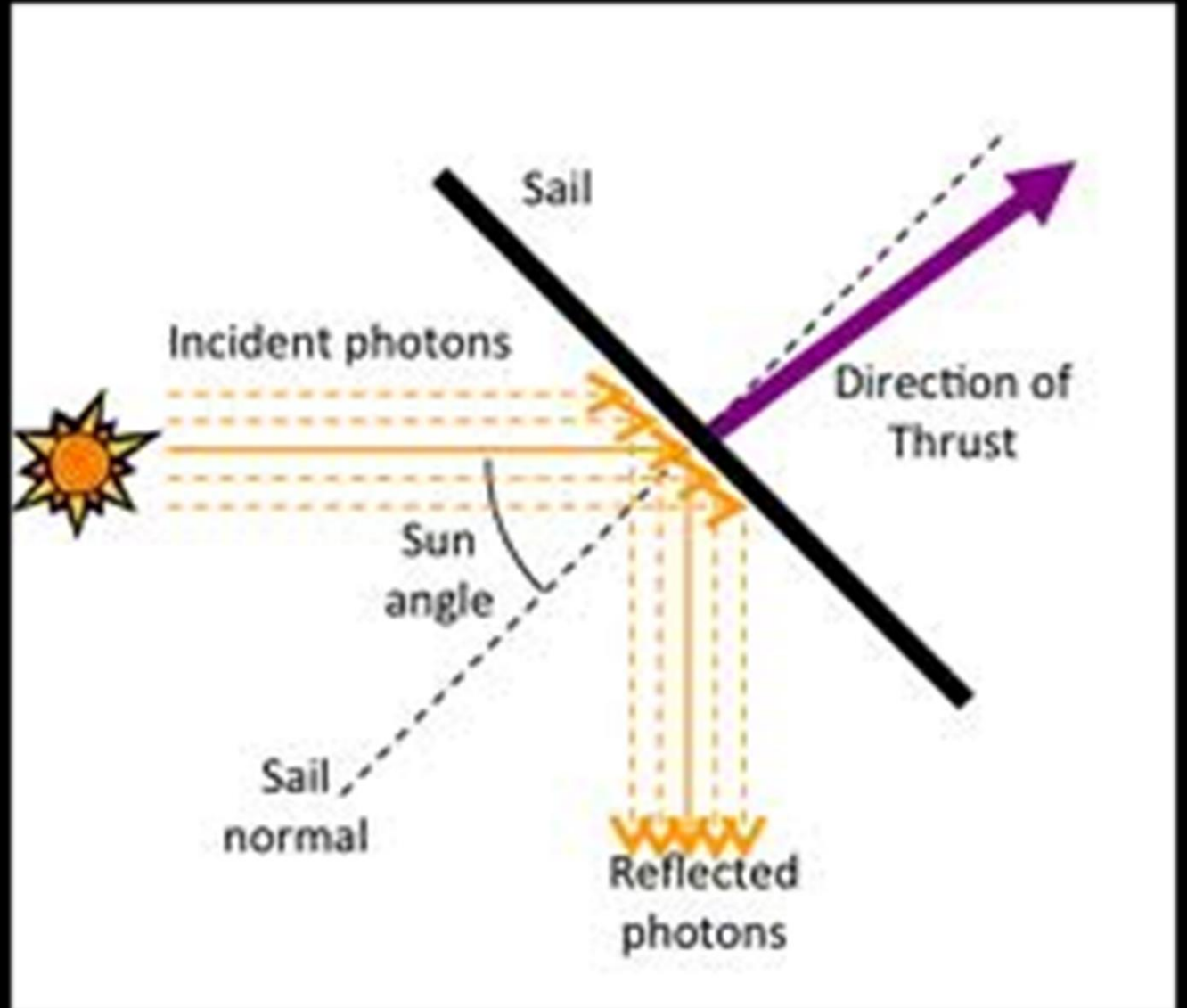
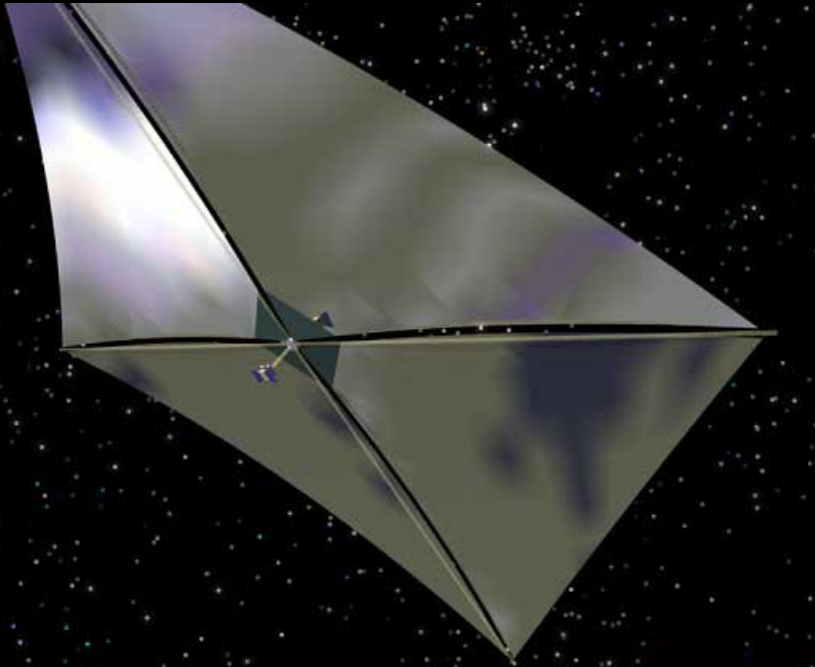
Can we use the environments of space to our advantage?





Yes we can! With solar sails...

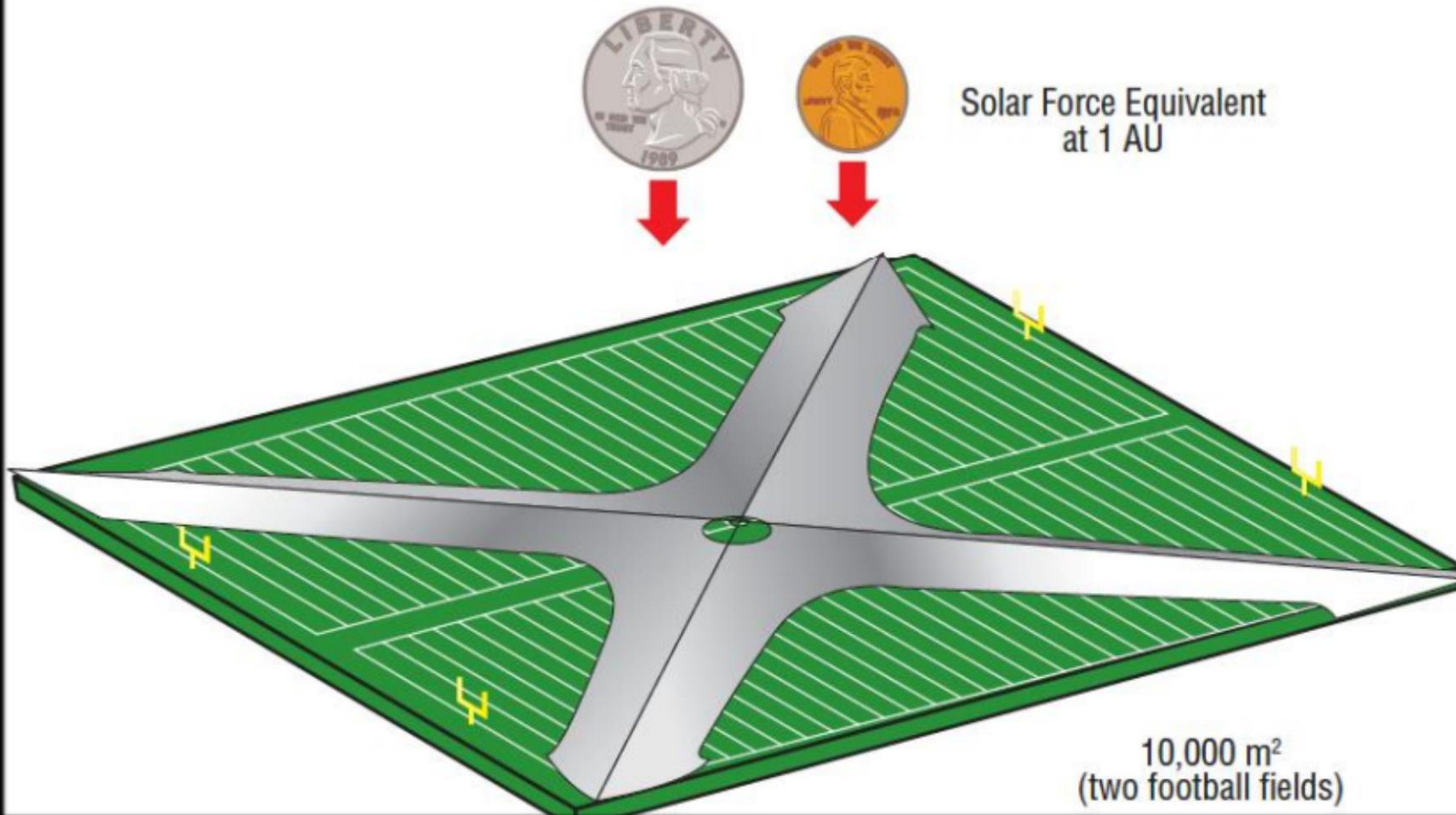
Solar sails use photon "pressure" or force on thin, lightweight, reflective sheets to produce thrust.





Solar Sails Experience **VERY** Small Forces

- Force on a 100 m x 100 m square sail:





Solar Sail Propulsion Fundamental Physics

- **Photons carry Momentum**

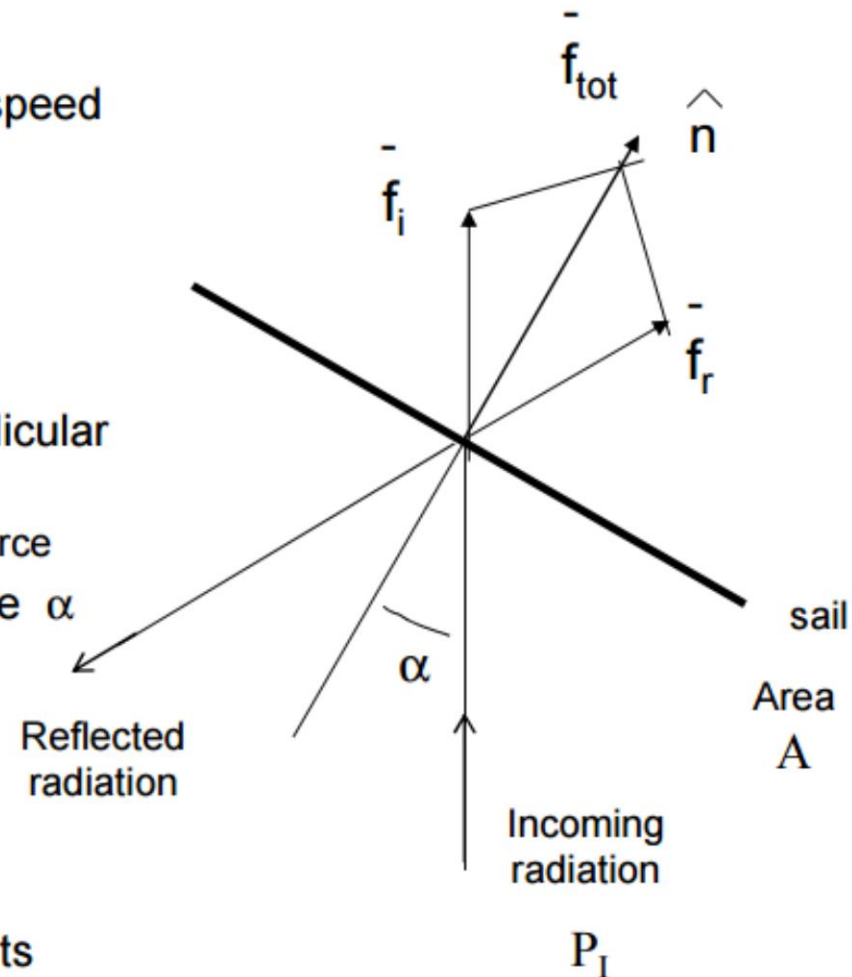
- $p = hv/c$
 - h = Planck's, v = frequency, c = speed of light

- **Force generated on Reflective Surface**

- Resultant force approximately perpendicular to surface
 - The bigger the surface, the more the force
- Can “steer” sail by changing pitch angle α

- **Small, but potentially Constant Acceleration**

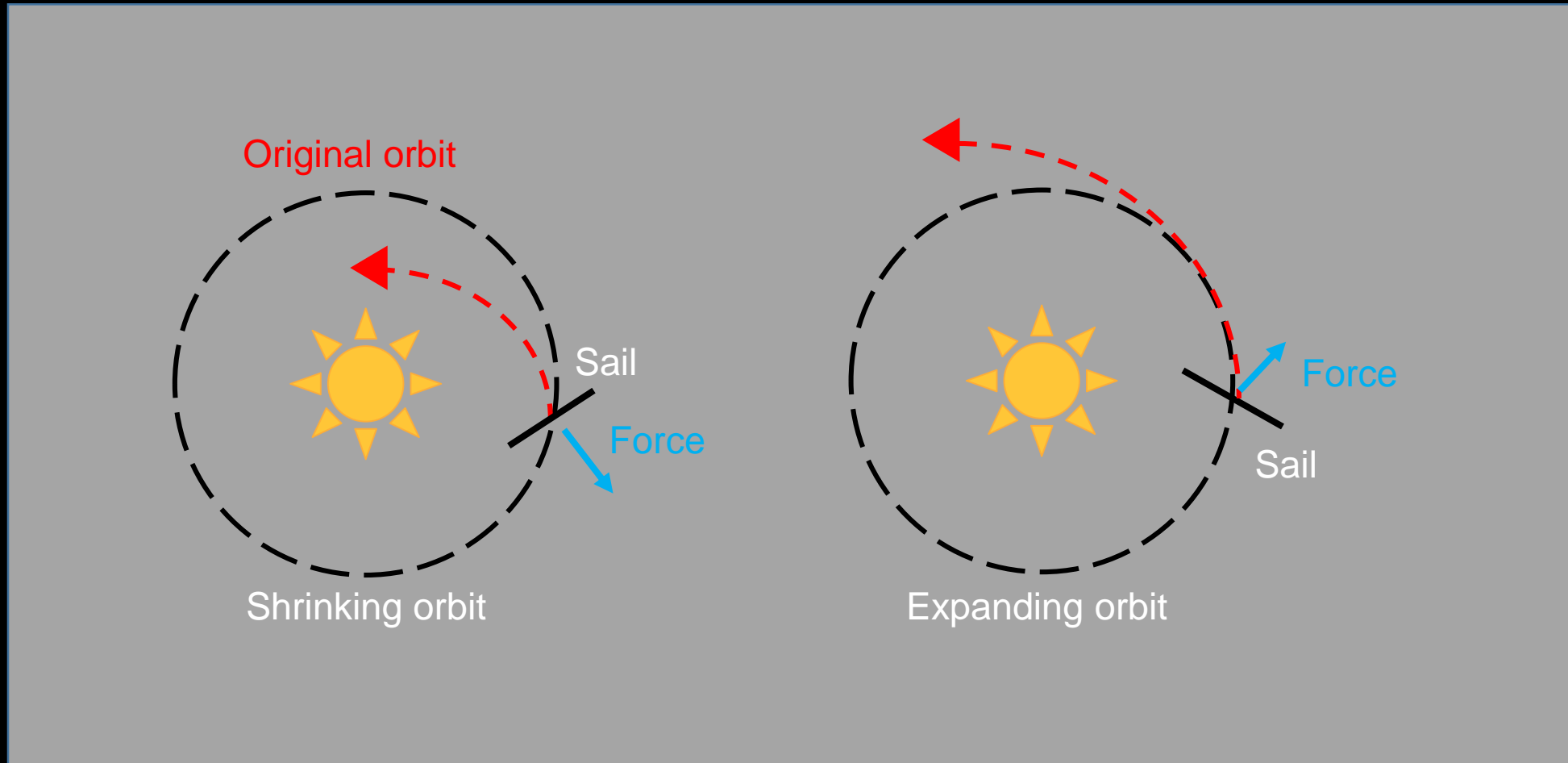
- Potentially unlimited “delta V”
- Allows some otherwise impossible orbits





Solar Sail Trajectory Control

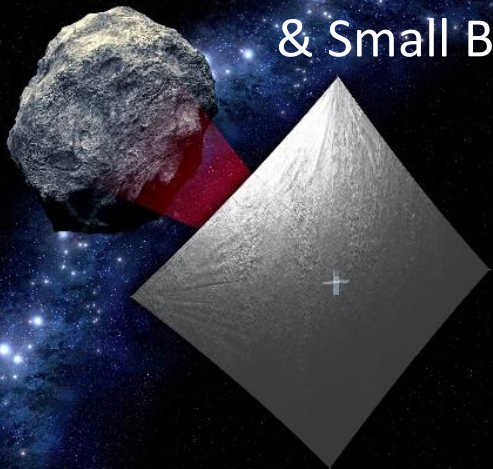
- Solar Radiation Pressure allows inward or outward Spiral



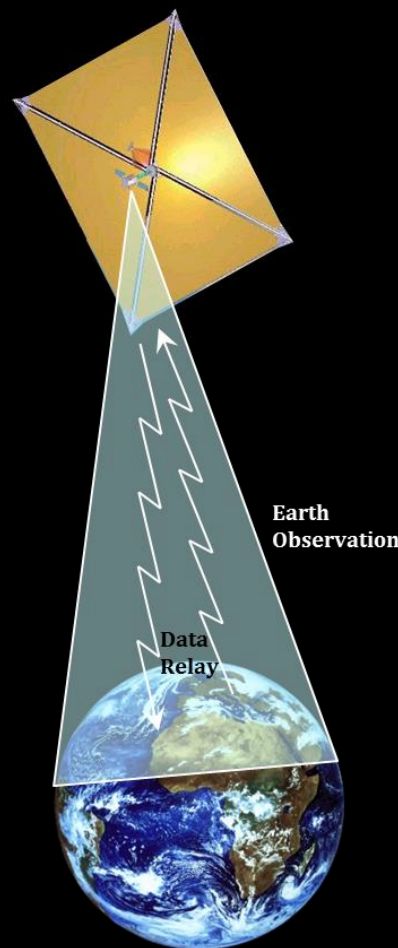


Potential Solar Sail Applications (A Partial List!)

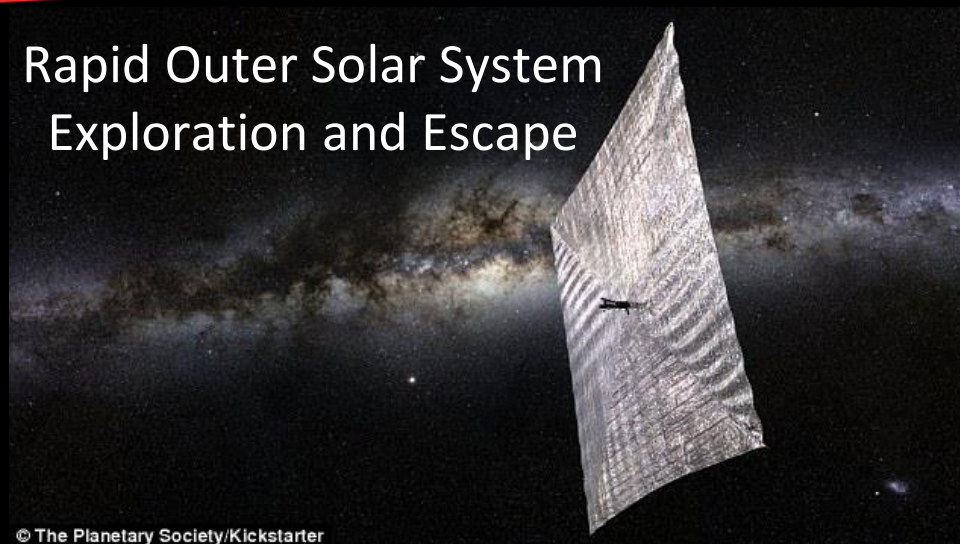
NEA Reconnaissance
& Small Body Science



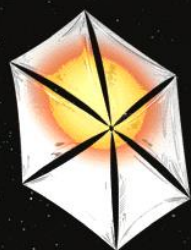
Earth Pole Sitting



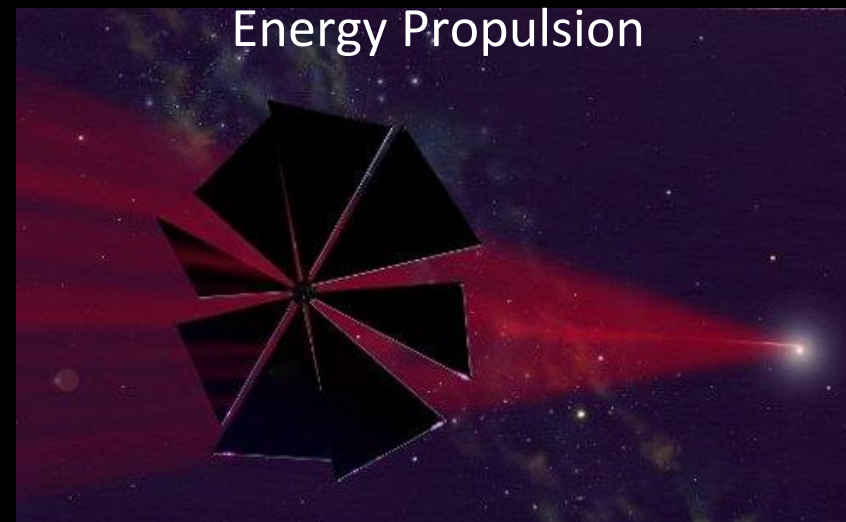
Rapid Outer Solar System
Exploration and Escape



Heliophysics & Out of
the Ecliptic Science



Toward Higher Performance Beamed
Energy Propulsion





Echo II 1964

Solar thrust effect on spacecraft orbit



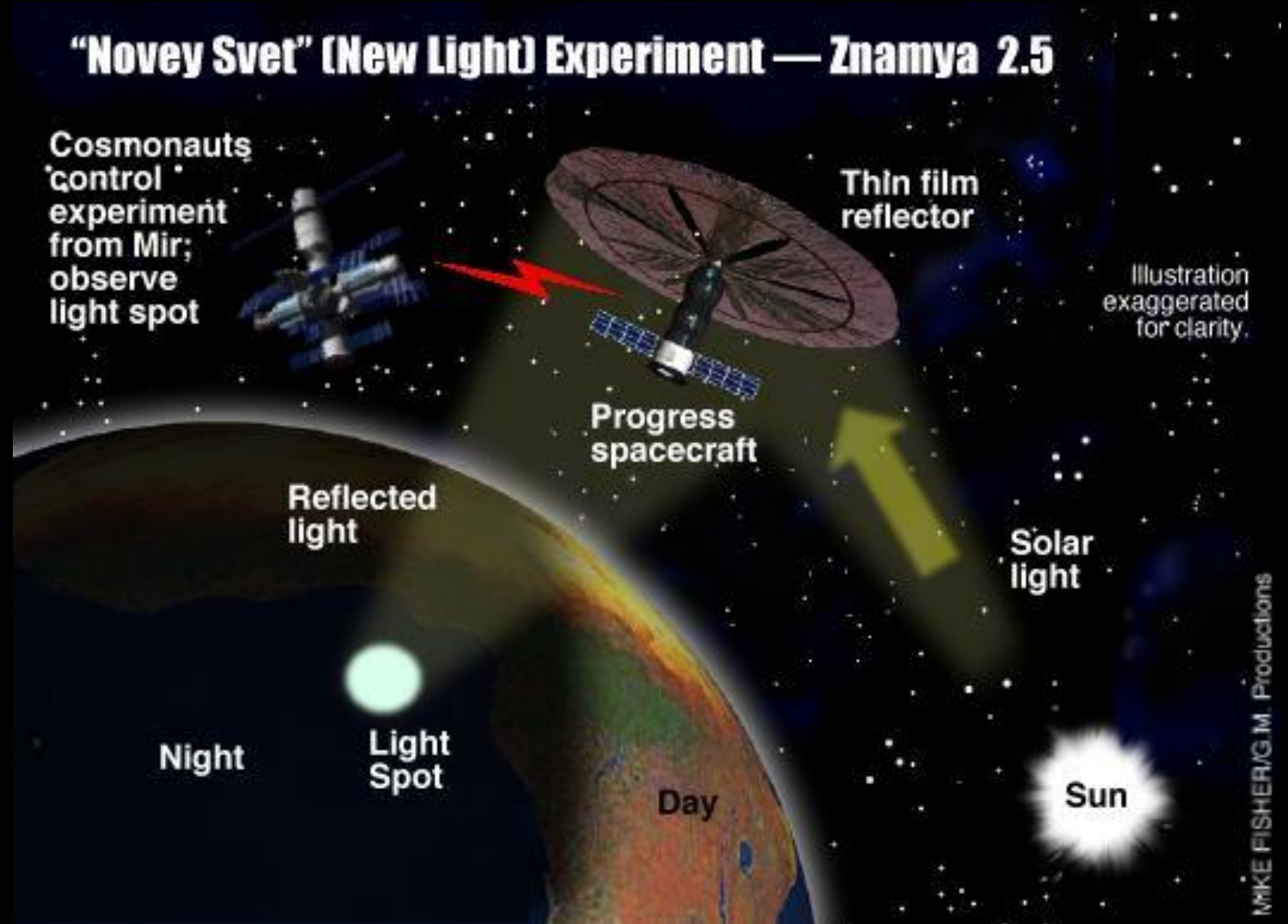
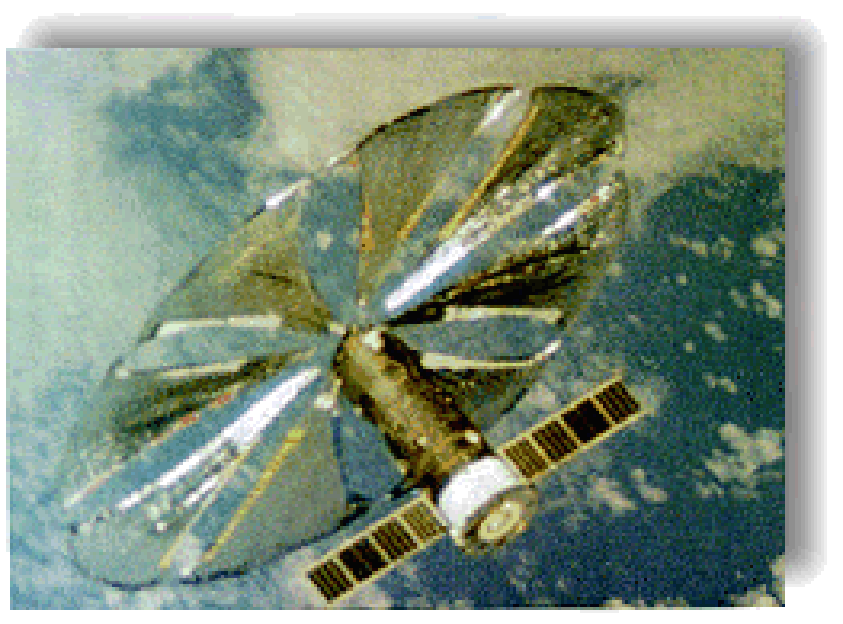
When folded, the satellite was packed into the 41-inch diameter canister shown in the foreground.

- 135-foot rigidized inflatable balloon satellite
- laminated Mylar plastic and aluminum
- placed in near-polar Orbit
- passive communications experiment by NASA on January 25, 1964





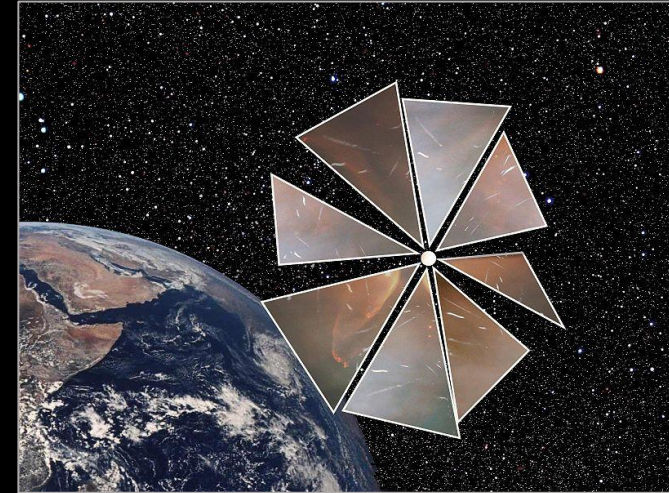
Znamya (Space Mirror)





The Planetary Society's Cosmos-1 (2005)

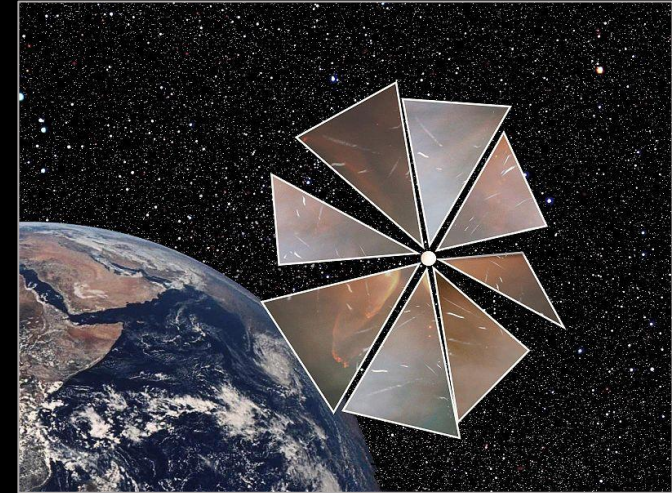
- 100 kg spacecraft
- 8 triangular sail blades deployed from a central hub after launch by the inflating of structural tubes.
 - Sail blades were each 15 m long
 - Total surface area of 600 m²
- Launched in 2005 from a Russian Volna Rocket from a Russian Delta III submarine in the Barents Sea.





The Planetary Society's Cosmos-1 (2005)

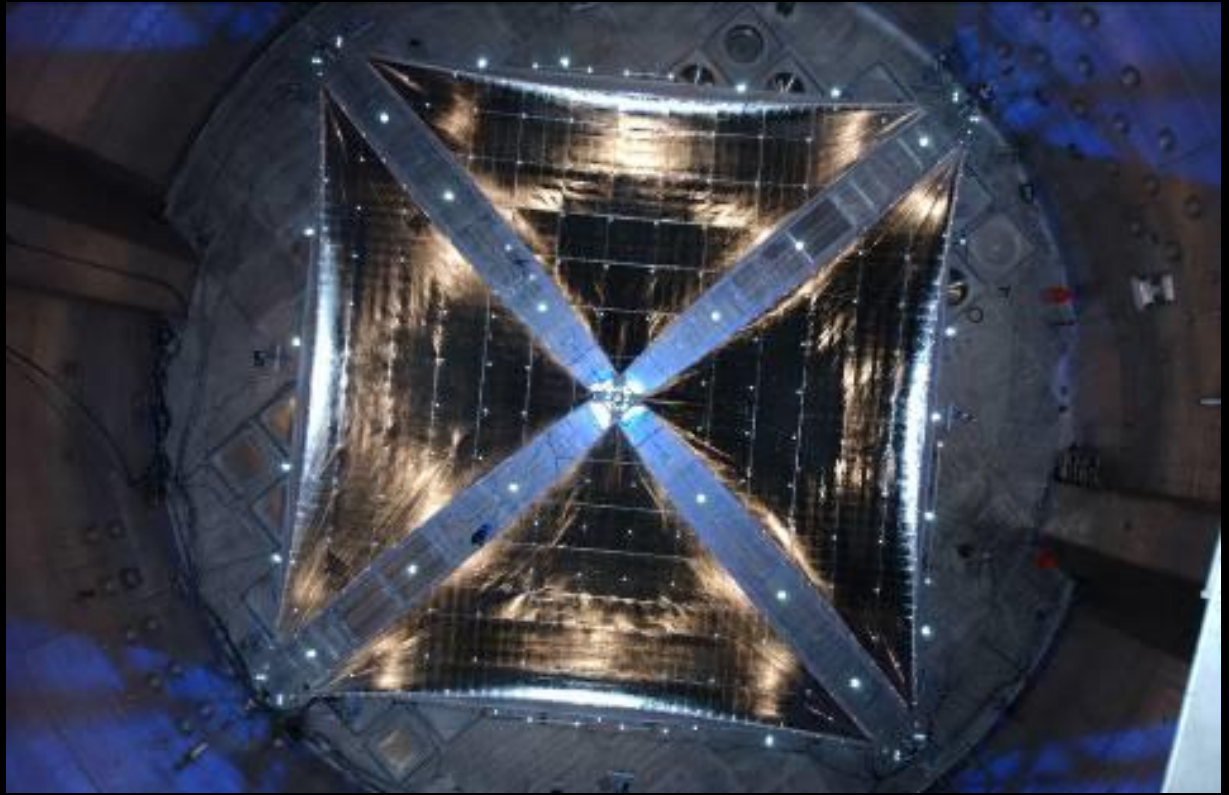
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 - Sail blades were each 15 m long
 - Total surface area of 600 m²
- Launched in 2005 from a Russian Volna Rocket from a Russian Delta III submarine in the Barents Sea.



Rocket Failed.



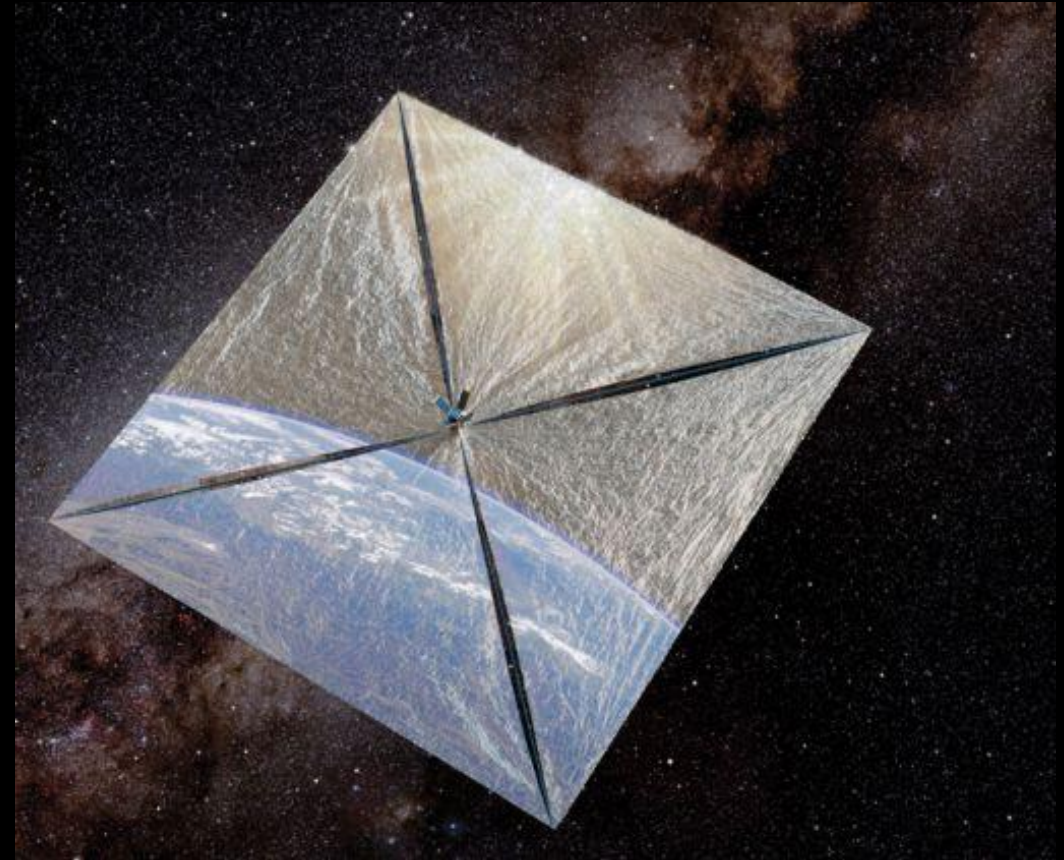
NASA Ground Tested Solar Sails in the Mid-2000's





NASA Space Technology Demo (2009)

- Planned to be a space flight demonstration of the solar sail
- developed and tested as part of the ground sail test program

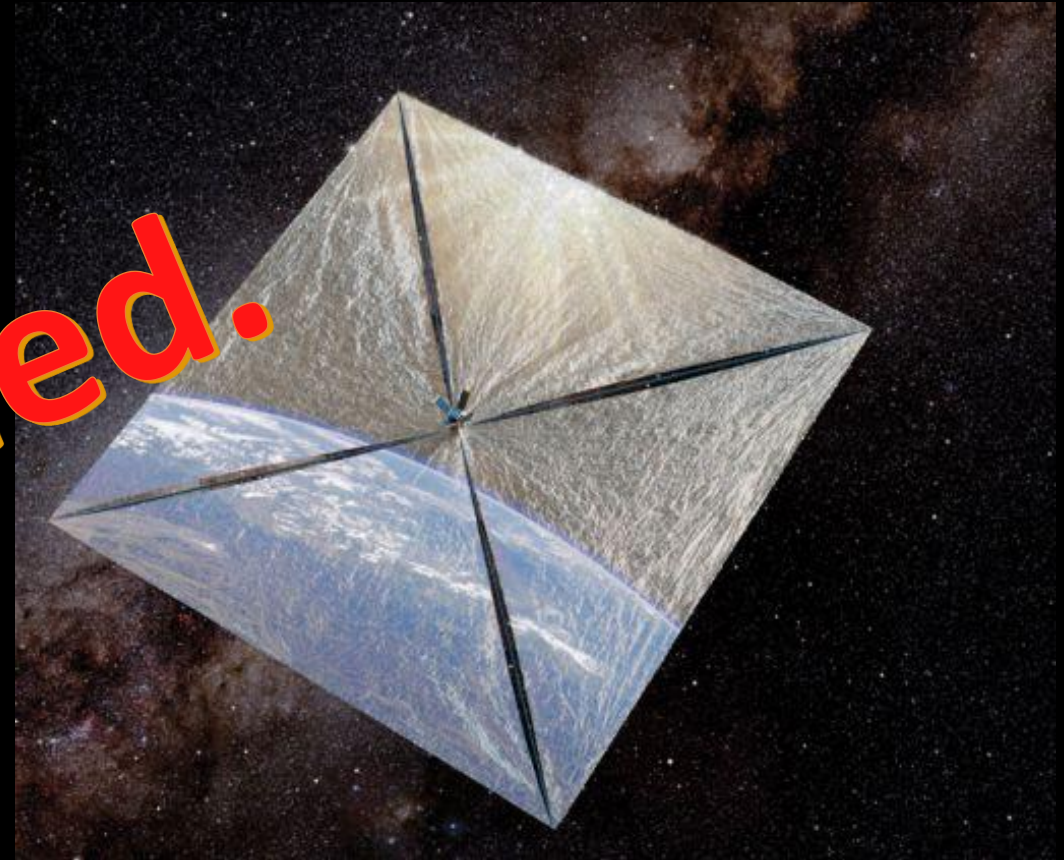




NASA Space Technology Demo (2009)

- Planned to be a space flight demonstration of the solar sail
- developed and tested as part of the ground sail test program

Cancelled.

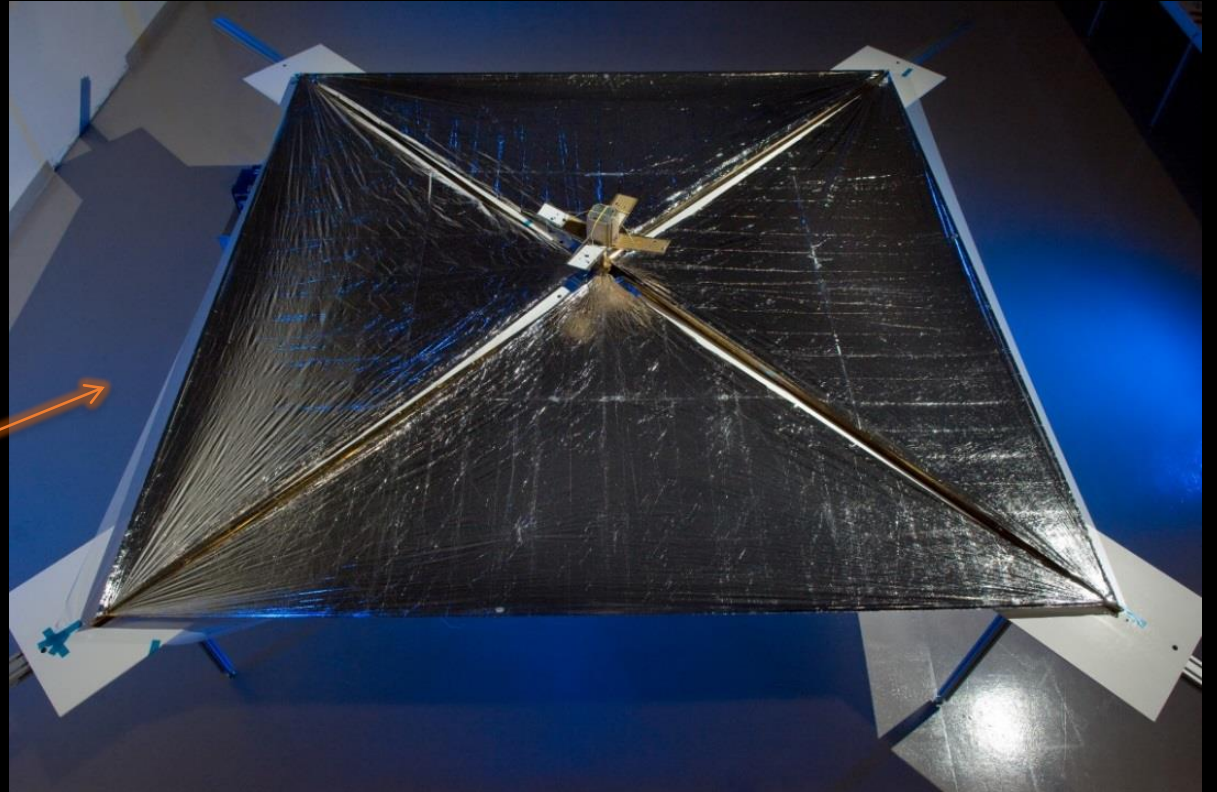
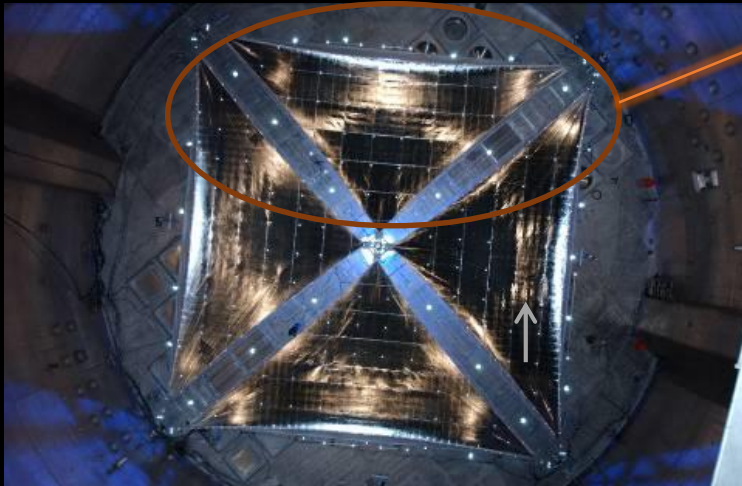




NanoSail-D Demonstration Solar Sail

Mission Description:

- 10 m² sail
- Made from tested ground demonstrator hardware

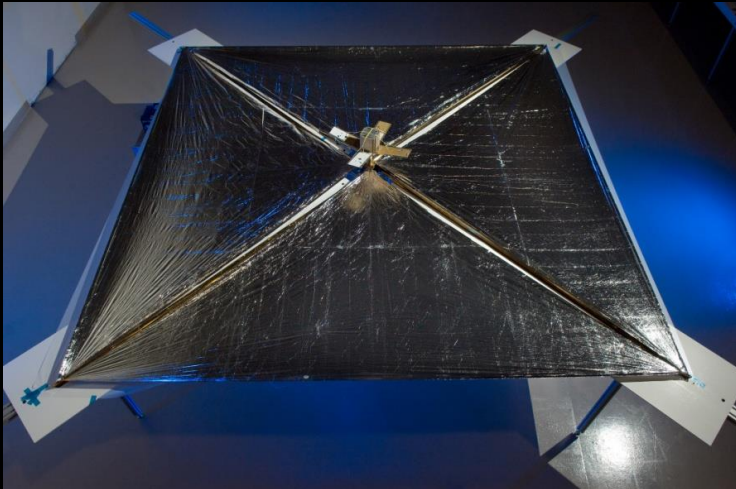




NanoSail-D1 Flight (2008)

Launch:

- Falcon-1, flight 3
- Kwajalein, Missile Range
- Primary payload: Air Force PnPSat



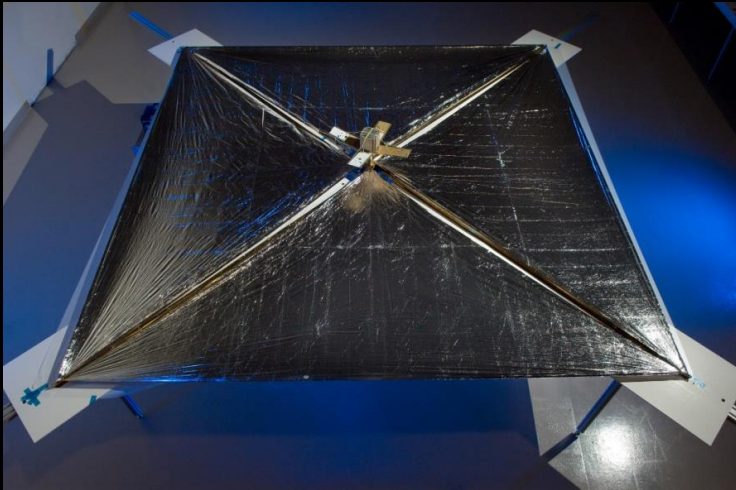


NanoSail-D1 Flight (2008)

Launch:

- Falcon-1, flight 3
- Kwajalein, Missile Range
- Primary payload: Air Force PnPSat

Rocket Failed.



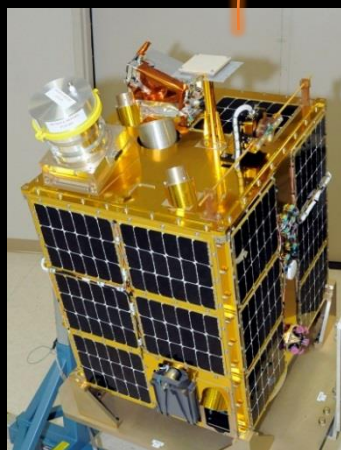


NanoSail-D2 Mission Configuration (2010)

3U CubeSat: 10 cm X 10 cm X 34 cm

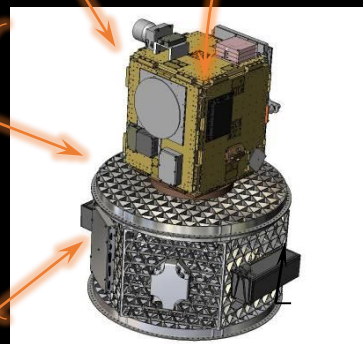
- Deployed CP-1 sail: 10 m² Sail Area (3.16 m side length)
- 2.2 m Elgiloy Trac Booms
- UHF and S-Band communications

Nanosail-D2 in Orbit August 19 2011 01h 19m 28s UT
Clay Center Observatory at Dexter and Southfield Schools
42.307404N, -71.13722W (WGS84)
www.claycenter.org Focal length: 12,200mm,
Aperture = 640mm Ritchey-Chretien
Contact: Ron Dantowitz (rondantowitz@gmail.com)



HSV-1

Adapter

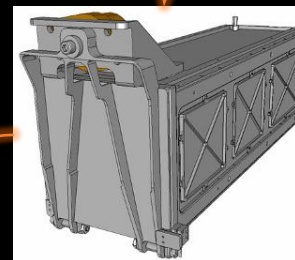


PreSat (ARC)

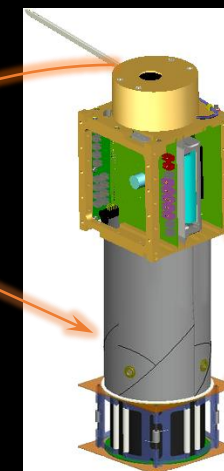
NanoSail-D (MSFC)

Ride Share Adapter
(Space Access Technology)

Boom & Sail
Spool
(ManTech SRS)



PPOD Deployer
(Cal-Poly)



Spacecraft Bus
(Ames Research Center)

Bus interfaces
Actuation
Electronics
(MSFC/UAH)

NanoSail-D
(Aluminum Closeout Panels Not Shown)

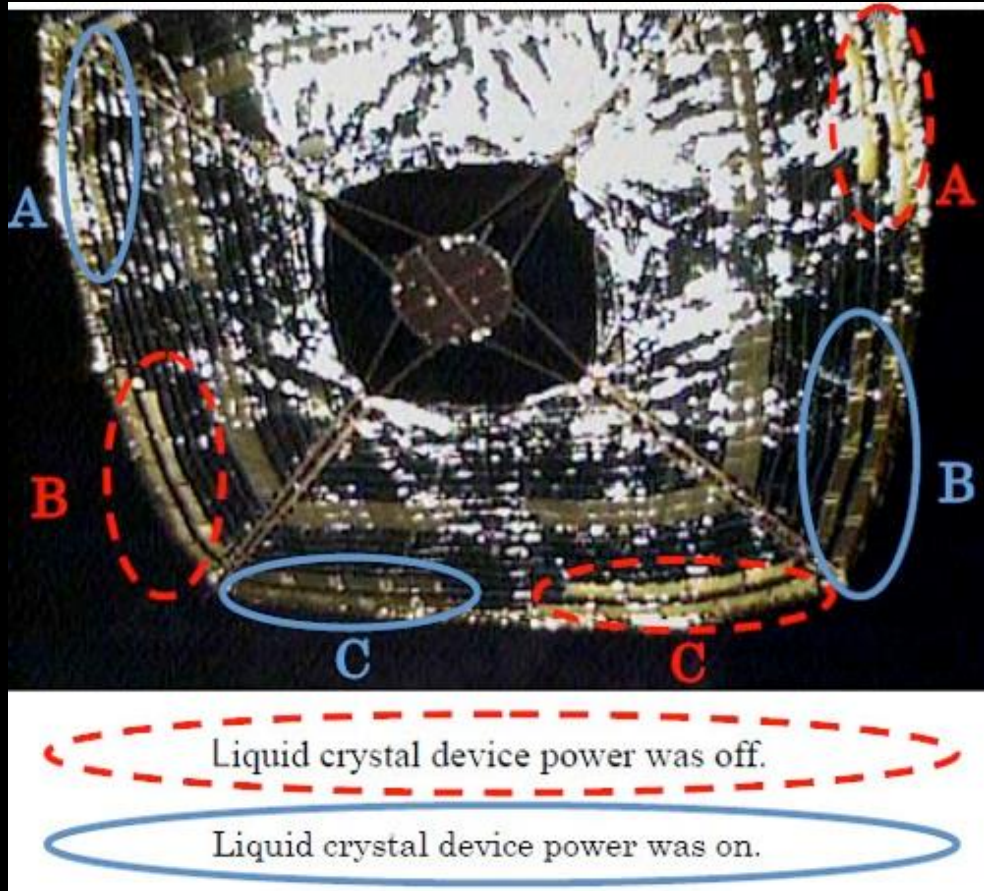
Stowed Configuration



NSD-002

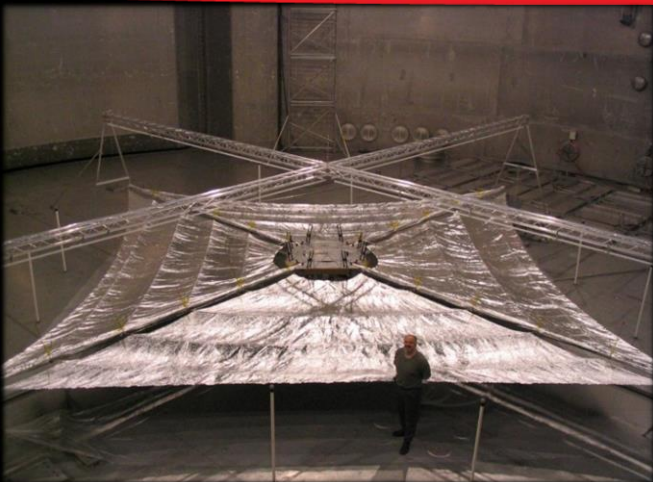
NSD-001

Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS)





Sunjammer Solar Sail Demonstration Mission



83 m² ISP L'Garde Solar Sail 2004



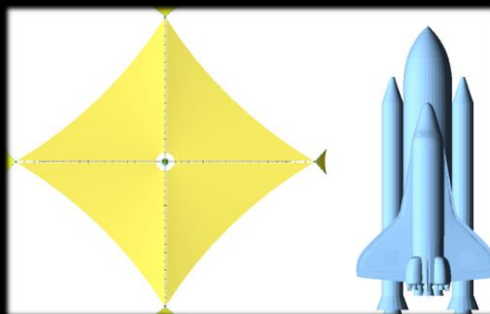
318 m² ISP L'Garde Solar Sail 2005

Design Heritage:

- Cold Rigidization Boom Technology
- Distributed Load Design
- Aluminized Sun Side
- High Emissivity Eclipse Surface
- Beam Tip Vane Control
- Spreader System Design

Design Features:

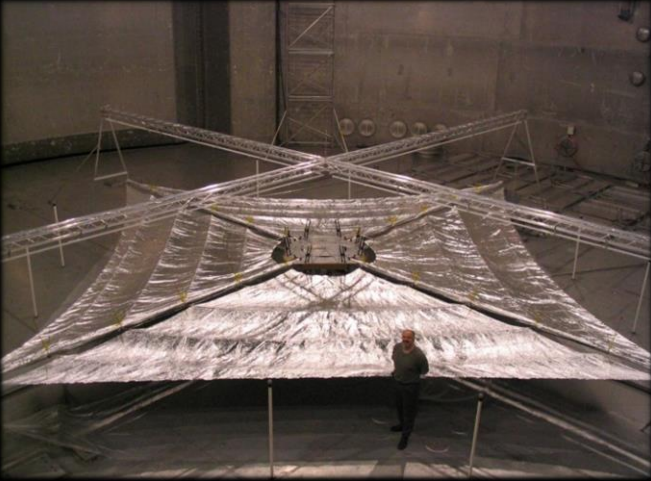
- High density packagability
- Controlled linear deployment
- Structural scalability
- Propellantless operation
- Meets current needs



1200 m² L'Garde Sunjammer Launch 2015



Sunjammer Solar Sail Demonstration Mission



83 m² ISP L'Garde Solar Sail
2004



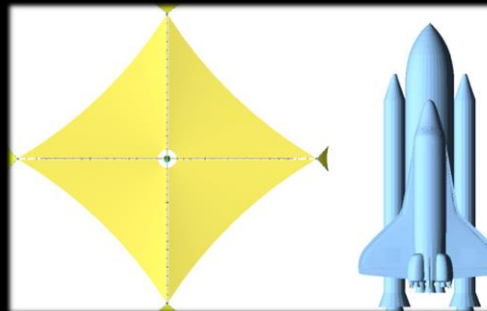
18 m² ISP L'Garde Solar Sail
2005

Design Heritage:

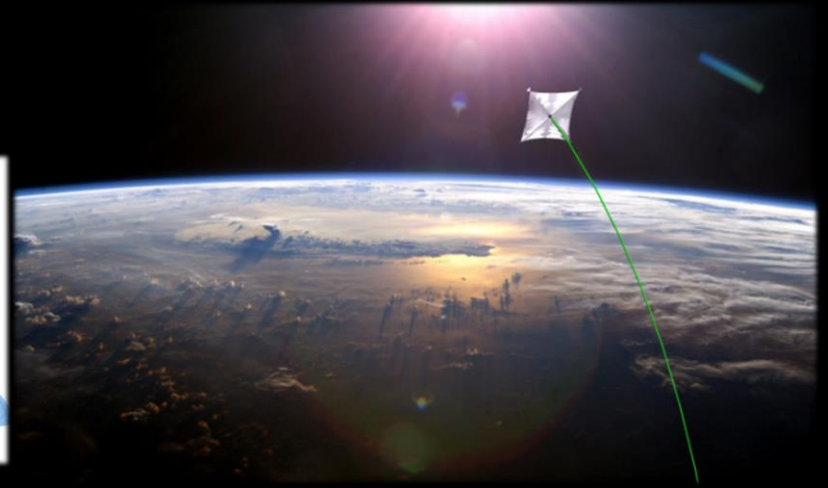
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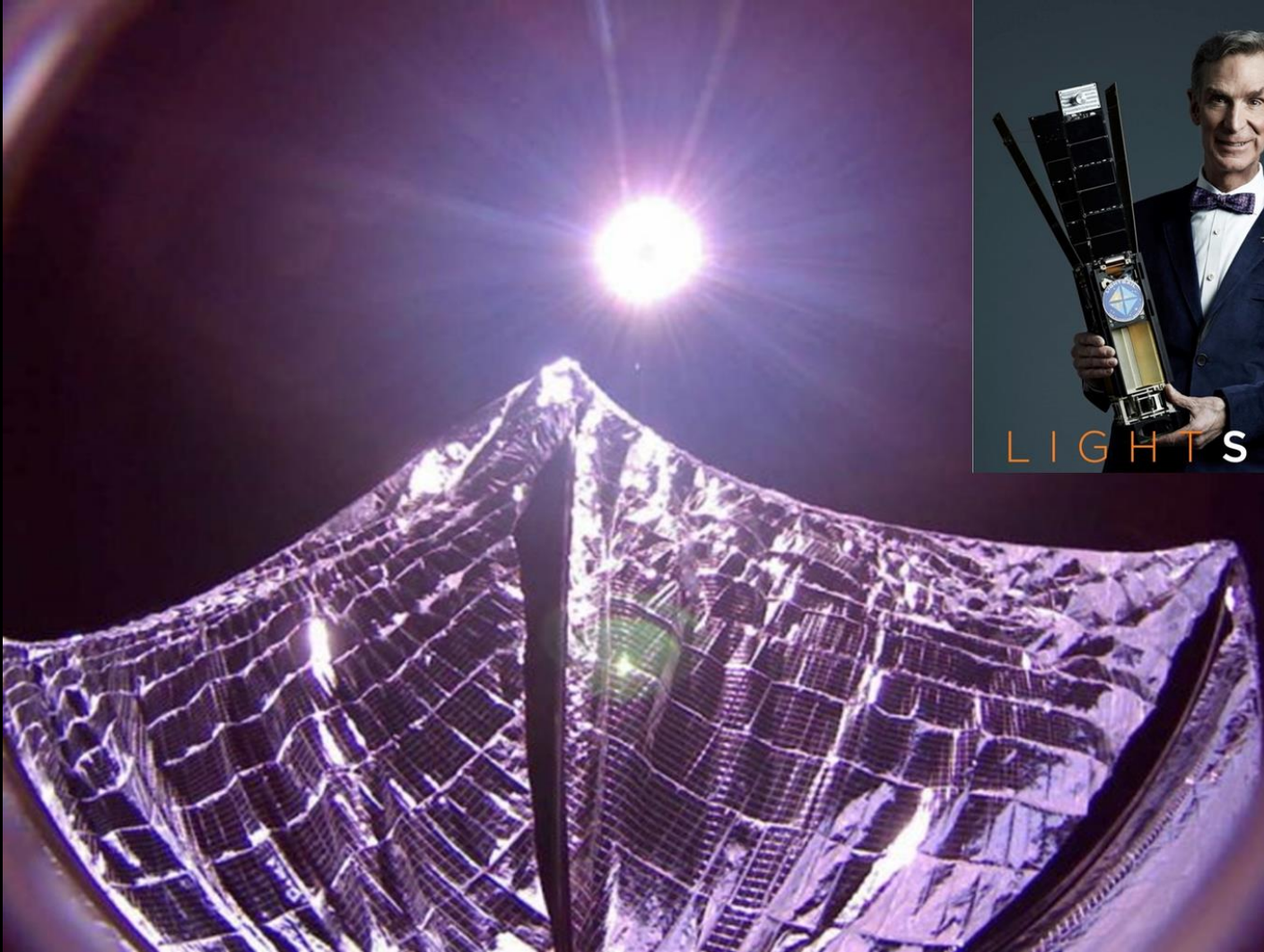
1200 m² L'Garde Sunjammer Launch
2015





Lightsail-A

(The Planetary Society)

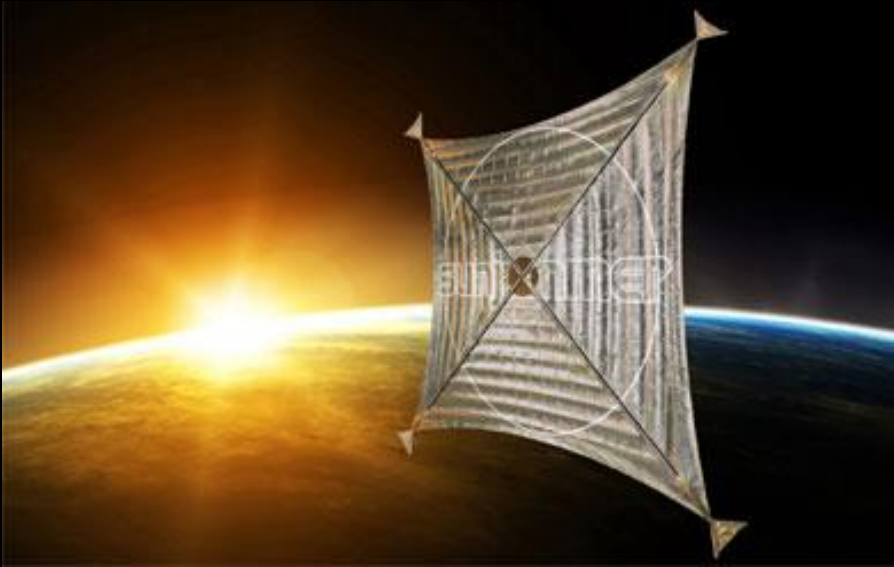


- 32 m²
- No active 'sailing'
- 3U CubeSat

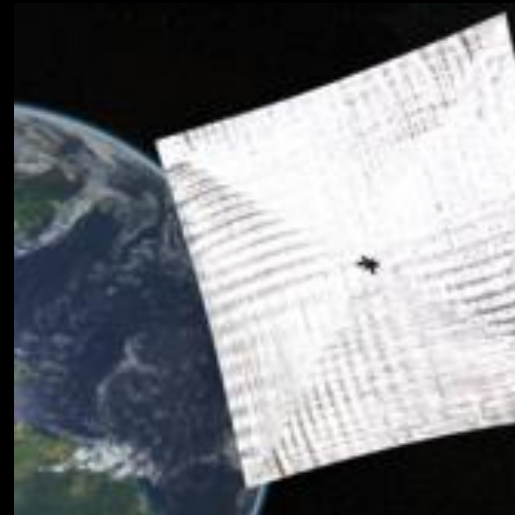
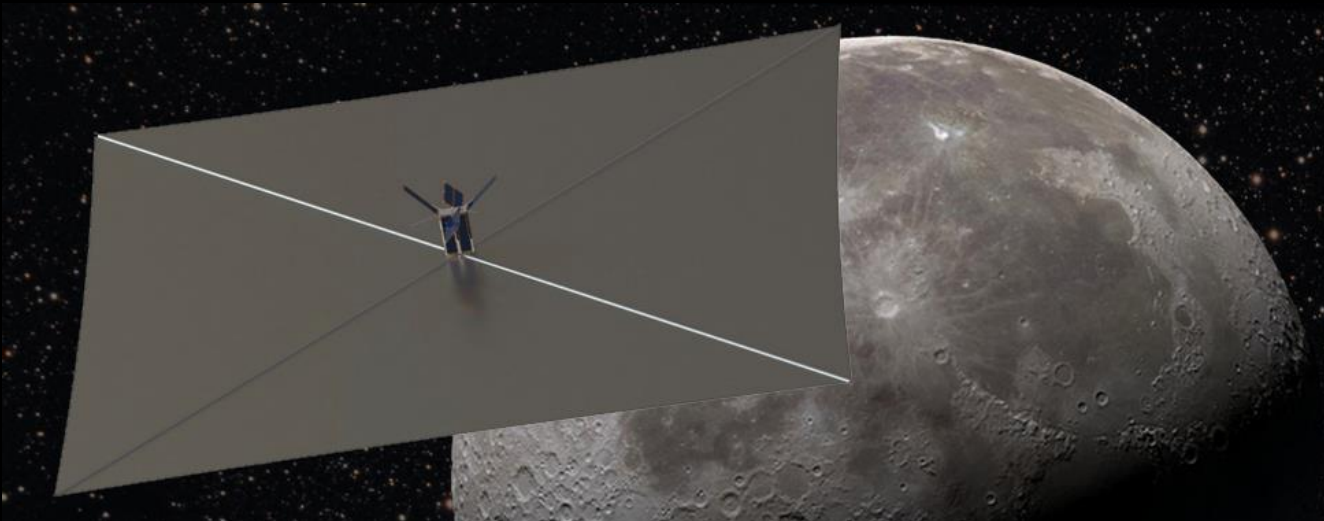
Flew successfully in 2015



Solar Sails **TODAY** – Many Missions Planned



- NASA's *NEA Scout*
- The Planetary Society's *LightSail-2*
- The University of Surrey's *InflateSail*
- University of Illinois' *CubeSail*





NASA's Near Earth Asteroid Scout

The Near Earth Asteroid Scout Will:

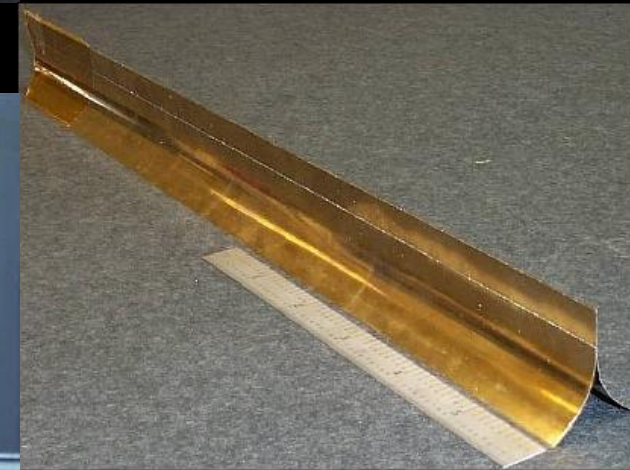
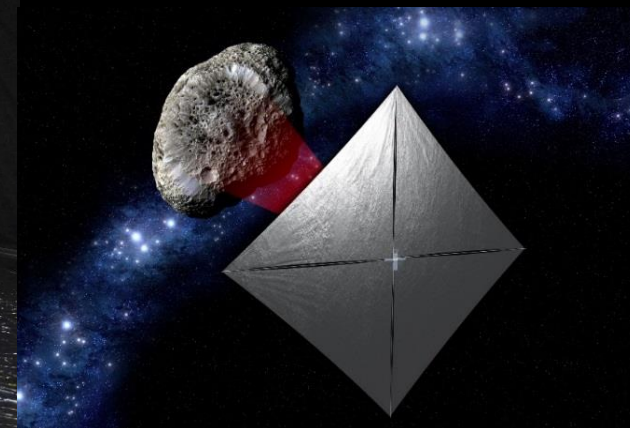
- Image/characterize a NEA during a slow flyby
- Demonstrate a low cost asteroid reconnaissance capability

Key Spacecraft & Mission Parameters

- 6U cubesat (20 cm X 10 cm X 30 cm)
- ~86 m² solar sail propulsion system
- Manifested for launch on the Space Launch System (EM-1/2017)
- Up to 2.5 year mission duration
- 1 AU maximum distance from Earth

Solar Sail Propulsion System Characteristics

- ~ 7.3 m Trac booms
- 2.5 μ aluminized CP-1 substrate
- > 90% reflectivity

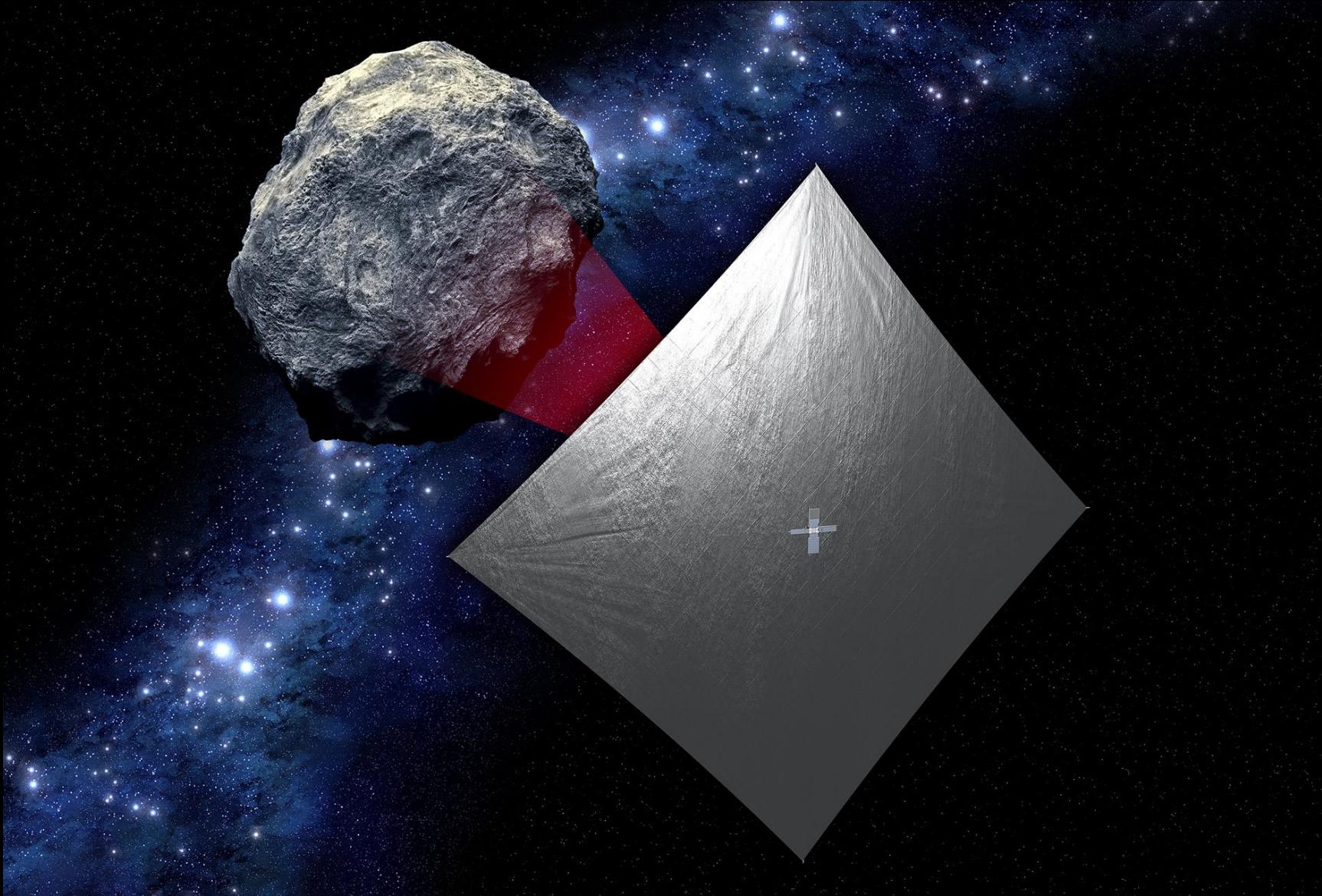




NEA Scout – Mission Overview



Near Earth Asteroid (NEA) Scout





NEA Scout Approximate Scale

Deployed Solar Sail



School Bus



6U Stowed
Flight System



Folded, spooled and packaged in here



University of Surrey's InflateSail

InflateSail is an inflatable, rigidizable sail for flight in Low Earth Orbit:

- 3U CubeSat with deployed sail area of 10 m²
- Sail supported by bistable booms
- Inflation is driven by Cool Gas Generators (CGG): low system mass, long lifespan

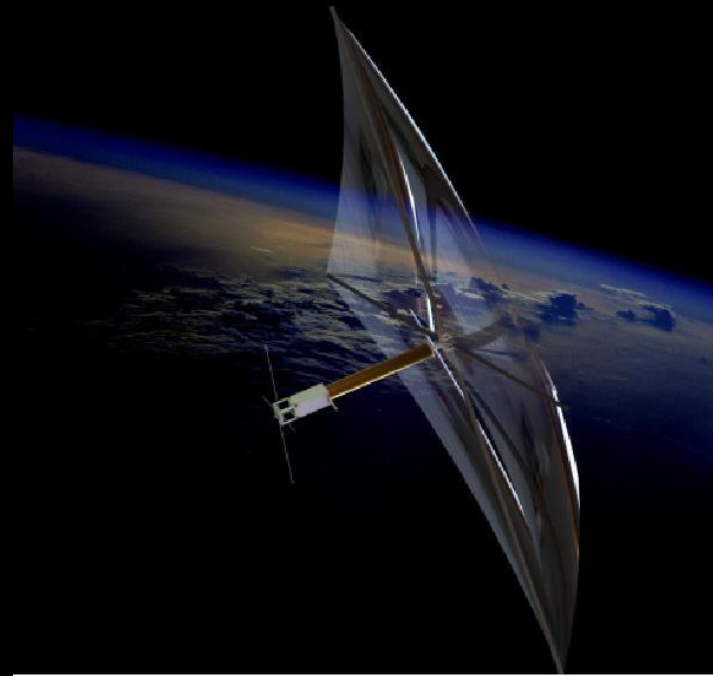


Fig. 1: InflateSail design concept



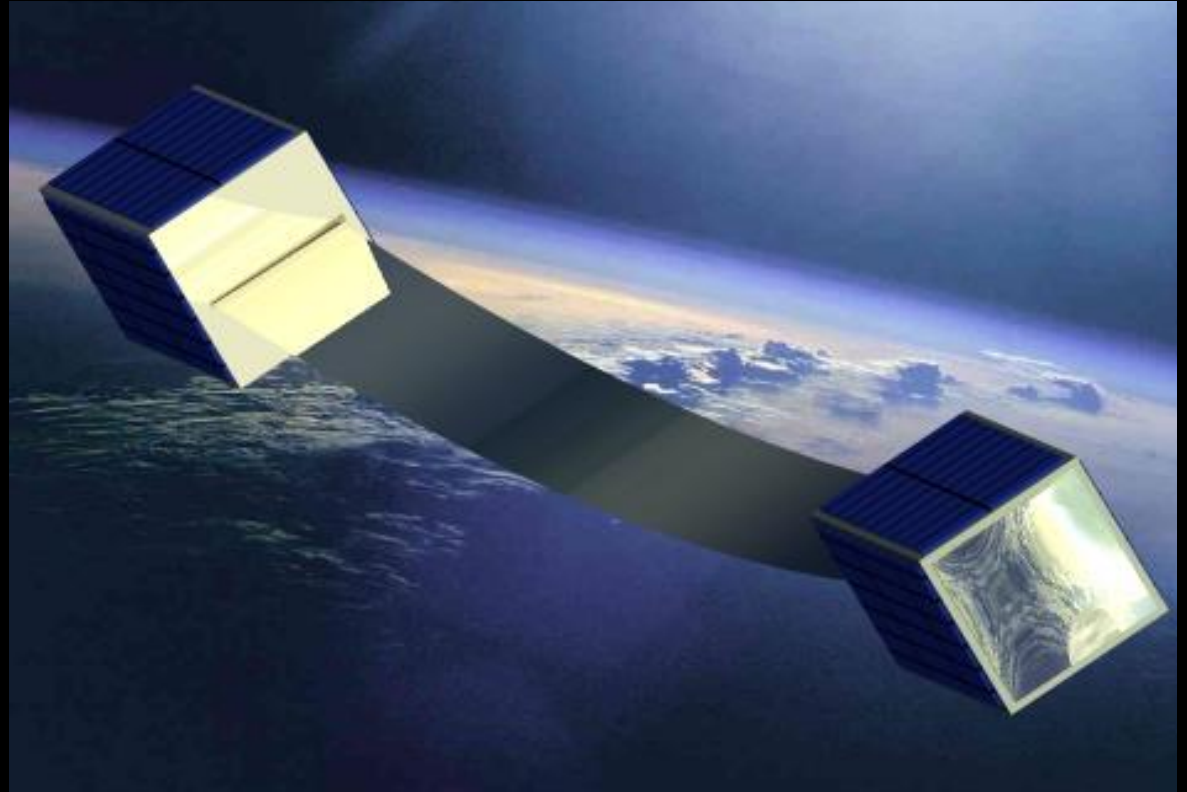
Fig. 2: 80 mg CGG George C. Marshall Space Flight Center





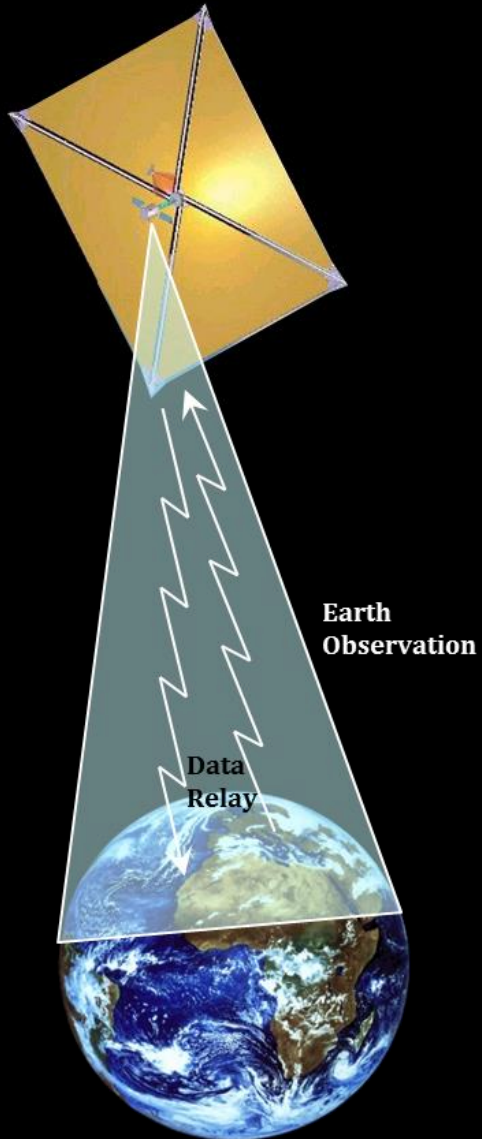
Cubesail CubeSat Solar Sail Propulsion Demonstration

- The University of Illinois at Urbana-Champaign (UIUC), working with NASA MSFC, NSF, and CU Aerospace, built the flight hardware for a CubeSat-based 20 m^2 solar sail orbit raising demonstration mission
- Selected for flight under the NASA CubeSat Launch Initiative





Continuous Polar Observations



- Sailcraft over the polar regions of the Earth
- Sail tilted so the light pressure from the sunlight reflecting from it is exactly equal and opposite to the gravity pull of the Earth.



Interstellar Probe

Deploy a large ($>10,000 \text{ m}^2$) solar sail near the sun to enable travel 5X faster than Voyager

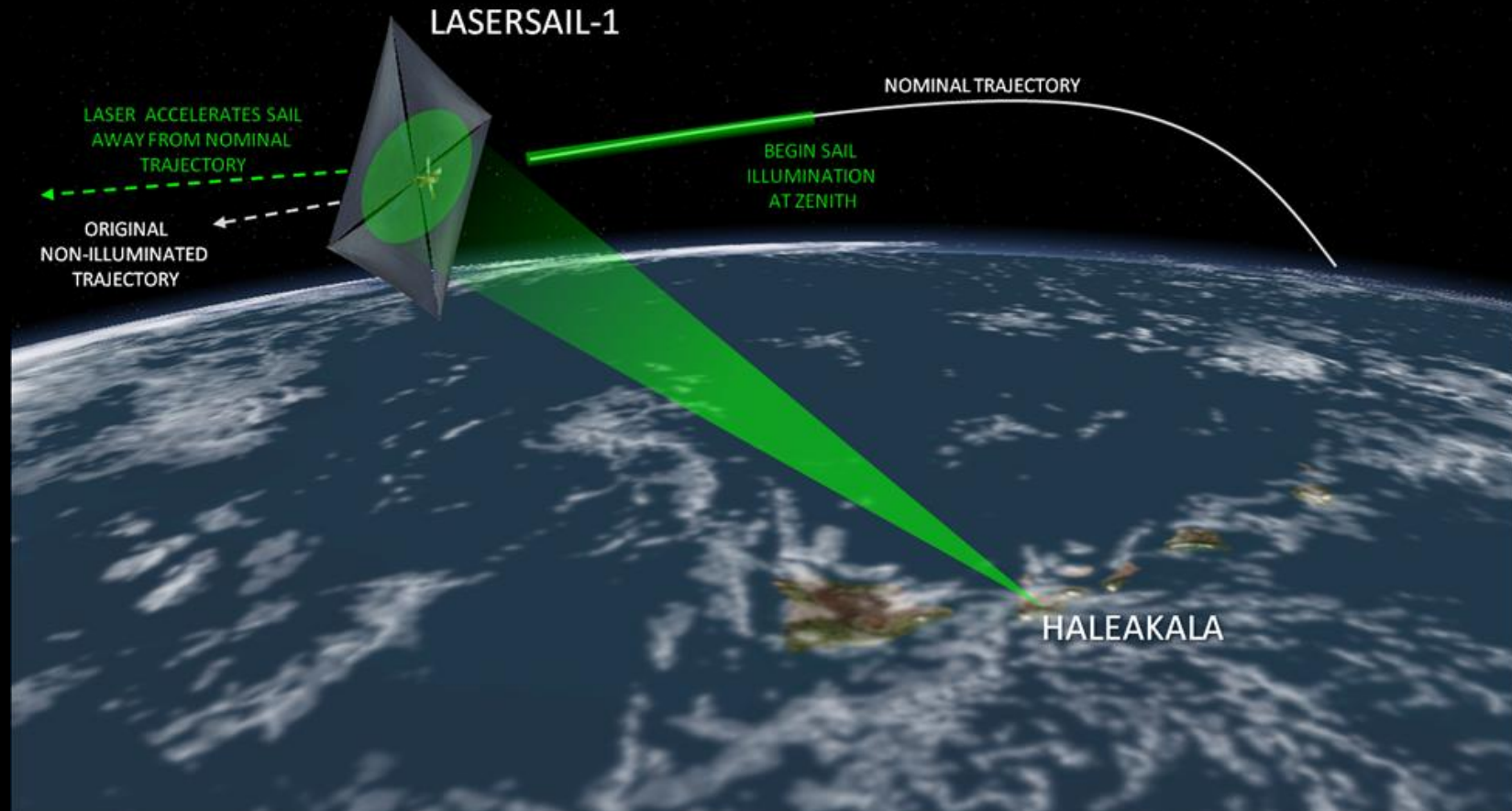


Goal: Reach 250 Astronomical Units within 20 years of launch



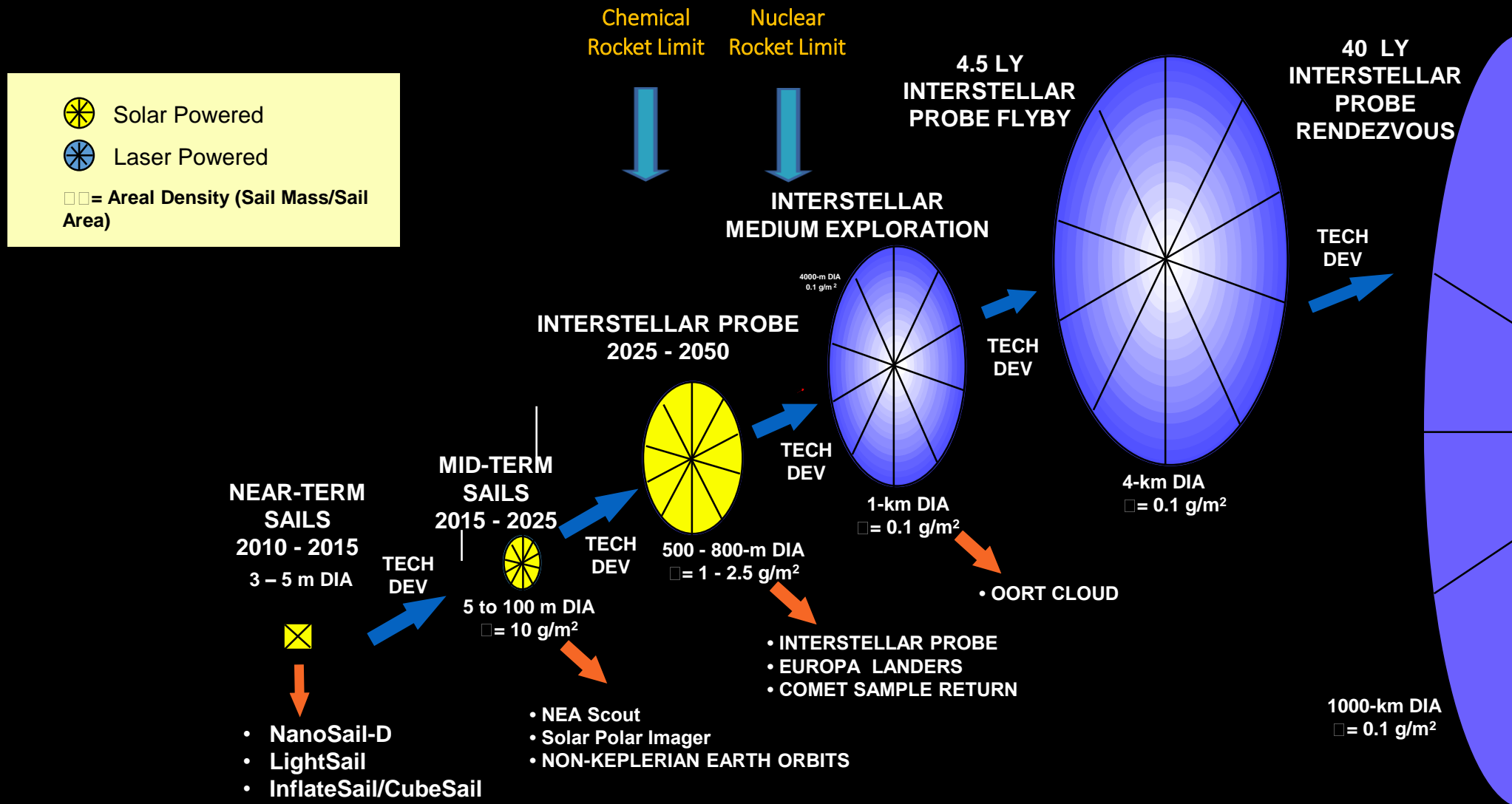
Laser Sailing: The Next Big Step

Ground to space laser illumination of a solar sail to impart measurable ΔV



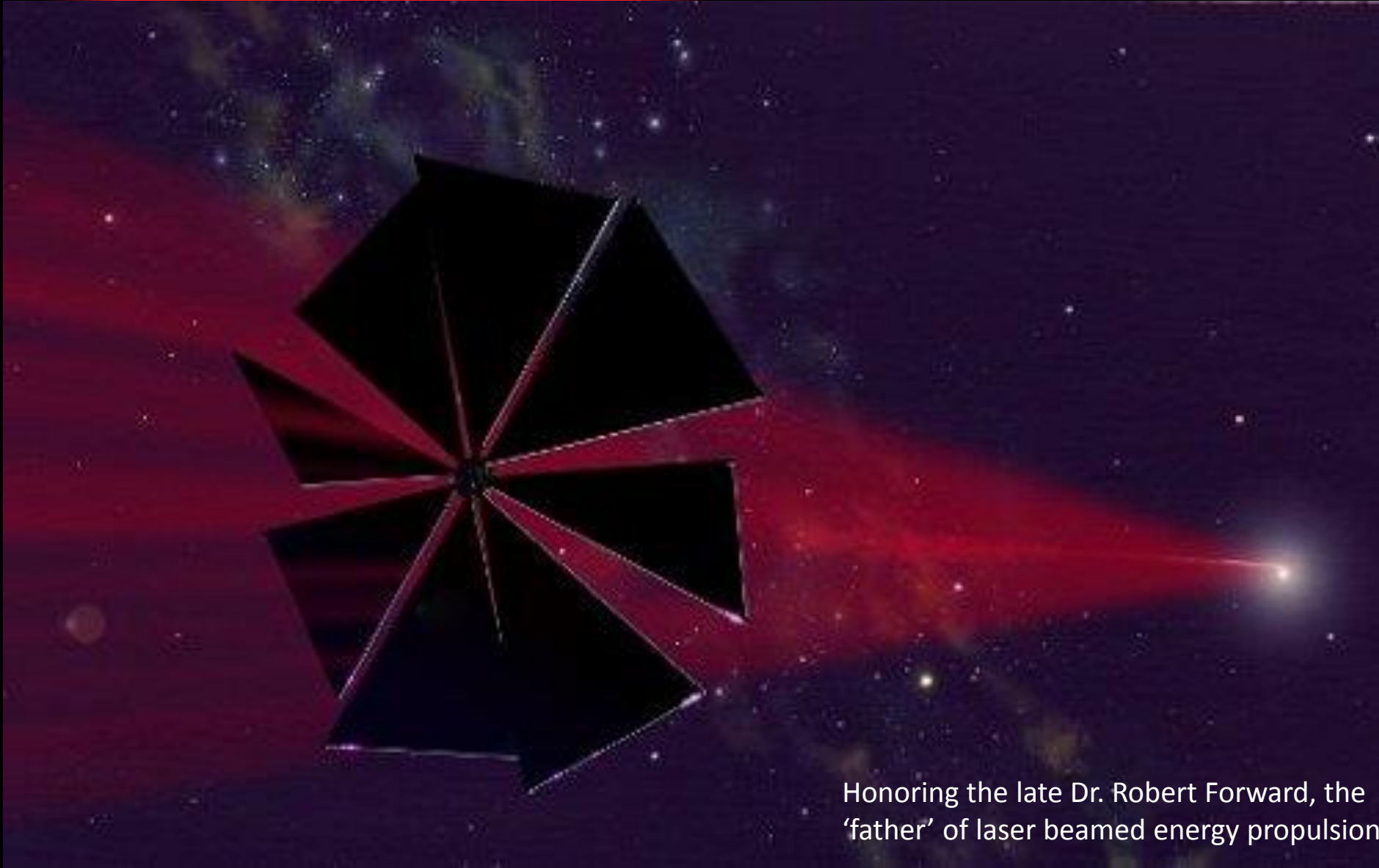


My Real Motive...





Solar Sails: A Step Toward the Stars



Honoring the late Dr. Robert Forward, the
'father' of laser beamed energy propulsion

